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14. ABSTRACT
Physical oceanography has moved into a new era, one in which there is a relative wealth of data from the Global Ocean Observing System. This system is comprised of both in situ instruments, such as Argo profiling floats, drogued drifters and moored arrays, and remote sensing satellites, such as altimeters and radiometers. Each of the datasets is valuable, yet each suffers inherent deficiencies. To make the most of these data, they need to be combined through optimal interpolation and via ssimilation into dynamical models. These statistical analyses are necessary steps in their quantitative use. A key ingredient of the statistical interpolation is the covariance between observable ocean state variables and the ocean circulation. The focus of this proposed research was to gain a better understanding of these multivariate covariances through the use of output from a global, eddy-resolving ocean general circulation model simulation. The result of the work will be better estimates of the covariance functions and from these, improved analyses of the ocean state and enhanced forecasting capabilities.

15. SUBJECT TERMS
Physical Oceanography, Interpolation, Dynamical Models, Statistical Interpolation, Ocean General Circulation Model Simulation, Forecasting Capabilities.

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Towards Improved Ocean State Estimation

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LONG-TERM GOALS

Determining the general circulation is a primary goal of oceanography, as is determining the role of the ocean in climate. These goals are closely related because the large-scale, time-mean circulation, together with its seasonal and inter-annual variations, substantially governs the mass, heat and salt fluxes on the planetary scale. The developing Global Ocean Observing System has at its core the sustained collection of a diverse set of observations of the ocean, and their synthesis into dynamically consistent maps of the three-dimensional velocity field and its associated transports of heat, salt and mass. Such analyses serve as tools to understand the ocean's dynamics and to provide metrics against which ocean models can be evaluated.

OBJECTIVES

The over-arching objective of this effort is to devise and produce empirical estimates of the large-scale ocean velocity field and its associated dynamic pressure field, over the full water column for the Atlantic Ocean using all of the observations available. To do this, the multivariate covariance functions for the ocean observations are required. It is the goal this effort to estimate those covariances using the output from an eddy-resolving ocean circulation model, and float and drifter observations.

APPROACH

The final product of these efforts will be estimates of three-dimensional velocity fields and the distributions of mass, heat, and salt for the ocean. We will make the estimates using the statistical techniques called objective mapping, which is based on the Gauss-Markov theorem. By using a partial set of dynamic constraints (e.g., interior geostrophy, conservation of mass, and no flow through topography), we can combine measurements of all the quantities to improve the circulation estimates without imposing all the constraints of a full dynamical model as is done in full data assimilation.

At the heart of any statistical interpolation of observations are the covariance functions that describe how the data related to each other in time and space. The focus of this work is to gain a better understanding of the multivariate covariance functions that apply to the observable ocean. Our approach is to use the output from state-of-the-art high-resolution ocean general circulation models to estimate these covariance functions. For this effort we utilize the output from the Parallel Ocean Program (POP) that is being run at 1/10° resolution spatial resolution.

TASKS COMPLETED

The work completed consisted of writing new diagnostic code that was inserted into the POP model simulations. To do this, the code was developed and tested at the Los Alamos National Laboratory (LANL) in collaboration with Frank Bryan (NCAR), Matthew Hecht (LANL), and Julie McClean (NPS). The PI spent one week at the Naval Postgraduate School in Monterey in the spring of 2003 working on the code with Julie and Frank (who was on sabbatical there from the NCAR).

In 2004 I accomplished compiling the model output needed to compute the covariances for ocean state estimation. This was done with code developed in collaboration with LANL, and then included in one of their high-resolution simulations of the North Atlantic Ocean. It was anticipated that global high-resolution output would be used as well, however that output has not been readily available. Other low-resolution model output was obtained from NCAR, (i.e. non-eddy resolving) POP model simulations which were also analyzed and found to be unrealistic. This made the path toward estimating the covariance functions clearer as it removed any doubt that only eddy-resolving model simulations are useful, and time was not spent analyzing non-eddy resolving simulations. Additionally, covariances from float observations in the North Atlantic Ocean were computed to provide ground truth for the model-derived covariances.

In 2005 I accomplished a study of the accuracy of the mean sea surface height when combined with the geoid undulations from the GRACE (Gravity Recovery and Climate Experiment) Mission data that was recently released. The circulation was then estimated from this pressure field assuming geostrophy. These estimates of the circulation were compared with surface drifters. Estimates of the deep circulation were also made through the combination of the surface pressure field with the density field computed from the climatological hydrography. These deep geostrophic circulation estimates were also compared against deep floats. Finally, circulation estimates combining the mean sea surface height referenced to the GRACE geoid and drifters were made (Figure 1). This is an important step since optimal interpolation works best with a good prior estimate.

RESULTS

Covariances from float observations in the North Atlantic Ocean were computed and compared to similar covariances from the model and were found to compare favorably to a simple analytic form of the covariance functions. They are significant because, though they are derived from observations, they can be explained by a relatively simple analytic function and geostrophy.

The ocean circulation derived from the temporal-averaged sea surface height, which is referenced to the recently released geoid (GGM02) from the Gravity Recovery And Climate Experiment (GRACE) mission was estimated (Jayne, 2006). The creation of a precise, independent geoid allows for the calculation of the reference gravitational potential undulation surface, which is associated with the resting-ocean surface height. This reference height is then removed from the temporal-averaged sea surface height, leaving the dynamic ocean topography. At its most basic level, the dynamic ocean topography can be related to the ocean's surface circulation through geostrophy. This has previously been impracticable due to large uncertainties in previous estimates of the Earth's geoid. It was found that the new GRACE geoid is significantly more accurate for use in estimating the ocean's circulation. Prior geoids included the temporal-averaged sea surface from altimeters as a proxy for the geoid, and therefore were unsuitable for calculations of the ocean's circulation. Error estimates were also made to assess the accuracy of the new geoid. The deep ocean pressure field was also estimated by combining the calculated dynamic ocean topography with hydrography. The derived circulation is compared to independent observations of the circulation from sea surface drifters and subsurface floats.

IMPACT FOR SCIENCE

With a better understanding of the multivariate covariance functions that are used for mapping ocean observations we can work towards improved ocean state estimates. Ocean state estimates are vital for assessing the skill of numerical ocean models, and they provide dynamically consistent estimates of the ocean's circulation field for use in scientific studies.

The development of these techniques for ocean state estimation is also important for data assimilation efforts such as Global Ocean Data Assimilation Experiment (GODEA), the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS), the Hybrid Coordinate Ocean Model (HYCOM) data assimilation effort, and the Estimating the Circulation and Climate of the Ocean (ECCO) projects.

These results of this project are being written up in a series of manuscripts.

RELATIONSHIP TO OTHER PROGRAMS

This work is closely related to an effort funded by the National Science Foundation, whose principal investigators are Breck Owens and Steven Jayne (WHOI), Bruce Cornuelle (Scripps), Bill Large (NCAR) and Jim McWilliams (UCLA). This effort is developing the objective mapping techniques that will be used to produce the final maps of velocity and pressure. The covariance functions estimated from this ONR funded effort will be utilized in that objective mapping effort.

This work is also related to an effort funded by NASA, which I am the principal investigator on, the goal of which is to analyze and utilize the new geoids coming from the GRACE mission, and ultimately to estimate the time-evolving ocean state from GRACE, altimetry and the Argo program.

FIGURES

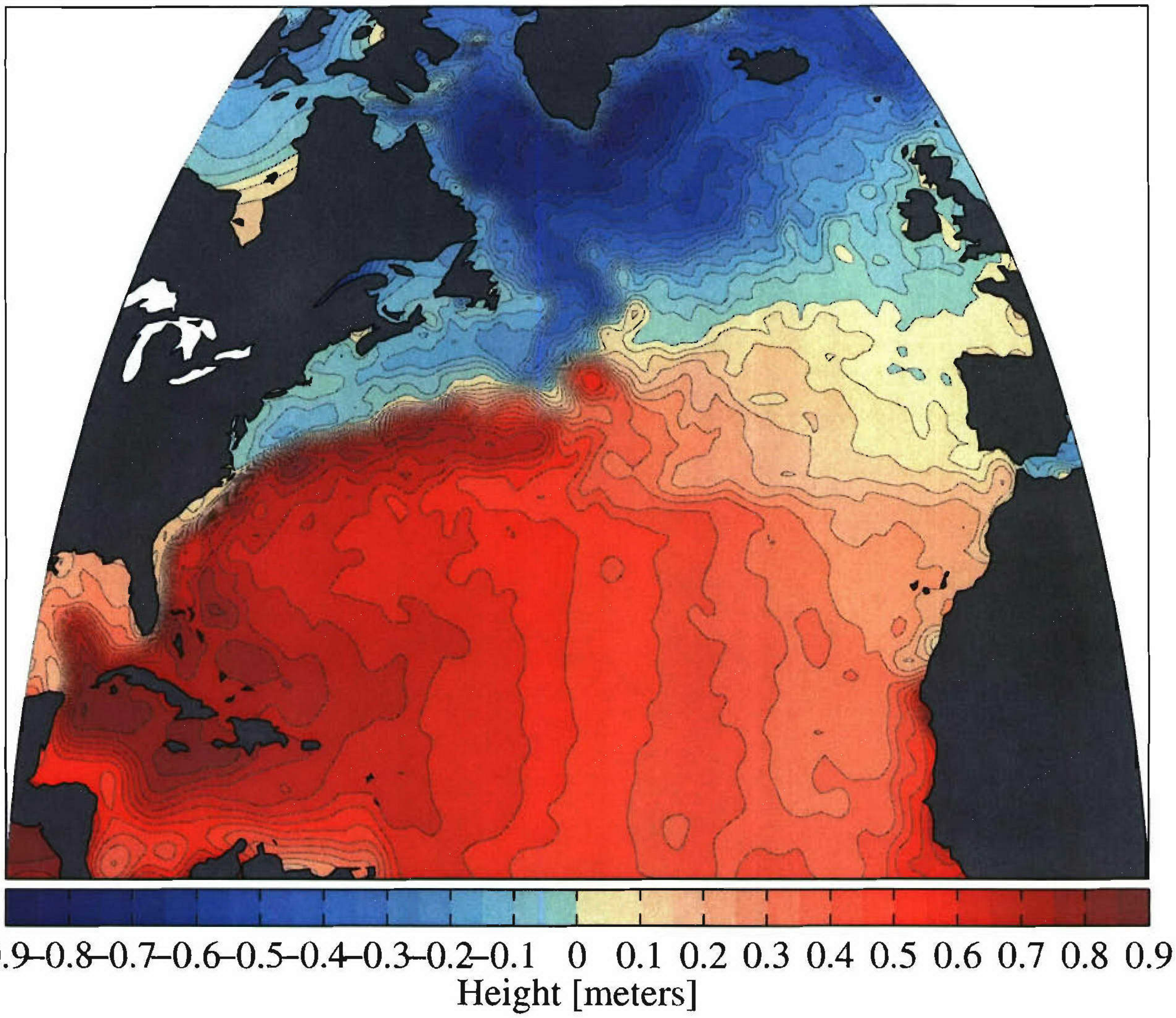

Figure 1: Estimated time-averaged sea surface height from satellite altimetry referenced to the GRACE geoid, combined with surface drifter data through objective mapping.

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